What makes [Ultra] Luminous Infrared Galaxies shine? Properties and environments of ULIRGs from the *AKARI* Deep Field-South

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ABSTRACT

[Ultra] Luminous Infrared Galaxies ([U]LIRGs) are a rare class of galaxies whose exact mechanisms of activity and very high dust luminosity are still under debate, with the mixed role of galaxy mergers, starburst and Active Galactic Nucleus (AGN) to be clarified. For 39 [U]LIRGs discovered in the *AKARI* Deep Field-South (Małek et al. 2017) we analyzed their properties and found that ULIRGs are more commonly associated with edge-on (Type 2) AGNs than LIRGs which may point out to the geometric factor in whether we detect an object as a ULIRG or LIRG. Next, we attempted to evaluate galactic density in their vicinity based on the Digital Sky Survey (DSS) data and dedicated follow-up observations by the South African Astronomical Observatory (SAAO) telescopes. We concluded that ULIRGs prefer environments with high but not extreme density while LIRGs are more often found also in denser environments. It may imply that ULIRGs appear most often in the environment of the cluster outskirts, where galaxy mergers are the most probable, and it supports the hypothesis that mergers play the crucial role in their activation.

1. INTRODUCTION

Luminous and Ultra Luminous InfraRed Galaxies (LIRGs and ULIRGs) are a rare class of objects with total absolute infrared (IR) luminosities significantly higher than that of average galaxies (above $10^{11} L_\odot$ for LIRGs, and above $10^{12} L_\odot$ for ULIRGs). They are known to be much more common at higher redshifts (Takeuchi et al. 2005), but they are also found in the local Universe. Extreme luminosities of these sources are attributed mainly to their extreme star formation with a possible significant contribution from an active galactic nucleus (AGN).

[U]LIRGs are often found in merging systems - at least in the local Universe (at high redshift it is less evident), and therefore mergers are often assumed to be a likely trigger of their activity (Veilleux et al. 2002). However, there is no consensus in the literature yet what is the exact mechanism of the extreme activity of [U]LIRGs; does a merger trigger both an AGN and star formation, which then develop independently? Or is there a direct link between them and if so - is it an AGN what initiates or stimulates the star formation? Is merger necessary to trigger an [U]LIRG or can an AGN play this role?

Then, one basic question related to [U]LIRGs is: what is the role of the AGN in their activity. Is AGN necessary to trigger both LIRGs and ULIRGs or do they coincide only sometimes? Is the AGN activity and its properties related to the properties of the host galaxy in this case?

The next question is whether [U]LIRGs are indeed activated by an interaction with other galaxy. Galactic mergers are well known to appear in the past much more often than today which might explain why ULIRGs are more commonly seen at high redshift. In the same time, we know that a probability that a galaxy undergoes a merger depends on its environment. Mergers do not happen often in places where the galaxy density is low and the probability of its close encounter with another galaxy is low. However, they are not highly probable in the highest density environments - e.g., in the centers of galaxy clusters - either, as high peculiar velocities of galaxies prevent them (Lin et al. 2010). The occurrence of such events should be most probable in medium to high, but not extreme, density environments, for example in the outskirts of galaxy clusters. Is it really the case? Until now, there is no consensus in the literature.

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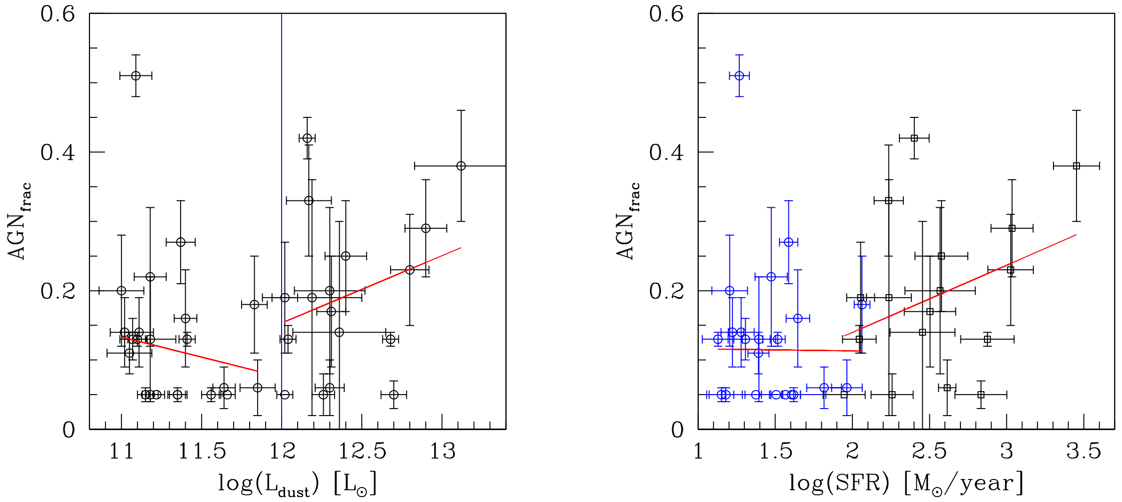

Figure 1. Left: AGN fraction as a function of a total dust luminosity for our ADF-S sample. Solid blue vertical line marks the division between LIRGs and ULIRGs. Red lines indicate linear trends estimated separately for these two groups. Right: AGN fraction as a function of star formation rate. LIRGs are marked by blue open circles, and ULIRGs as black open squares. Red lines indicate linear trends estimated separately for these two groups.

2. DATA AND METHODOLOGY

We used data from *AKARI* Deep Field - South (ADF-S) survey. The ADF-S covers an area of 12.6 deg^2, centered at $\alpha = 4^h44^m00^s$ and $\delta = -53°20'00''$. It has been observed in four *AKARI* far-infrared (FIR) filters centered at 65 μm, 90 μm, 140 μm, and 160 μm, which resulted in a catalog of more than 2,000 sources detected at 90 μm down to 20 mJy (Shirahata et al. 2009). Małek et al. (2010) cross-correlated the ADF-S sources detected at 90 μm and brighter than 30.1 mJy with public databases (SIMBAD, NED, IRSA) and created a multi-wavelength catalog of 545 objects with optical counterparts; for 183 objects from this catalog also spectroscopic data were found. After completing this catalog by additional data, among them from the Hershel FIR measurements, Małek et al. (2014) computed photometric redshifts for the ADF-S extragalactic objects making use of the CIGALE fitter (Noll et al. 2009; Serra et al. 2011).

For the analysis presented here the sample was further reduced to the redshift range $0.06 \le z \le 1.23$ (as the estimation of photometric redshifts below this value is less secure) and to galaxies with the best photometrically covered Spectral Energy Distributions (SEDs) and with at least one measurement in the FIR. For 27 galaxies *Herschel*/SPIRE measurements were included. This allowed us to estimate physical properties of 69 galaxies form this catalog with the most reliable data, based on SED fitting done by CIGALE (Małek et al. 2017).

Additionally, for each galaxy we estimated local projected density of galaxies around it based on the distances to the *n*-th neighbour (see Muldrew et al. 2012). For this measurements we made use of optical images - namely Digital Sky Survey (DSS) scanned plates, as this is the only publicly available optical survey covering all the ADF-S field. The DSS coverage sufficient for our measurements is available in two filters: B_j and R (APM Sky Catalogue photometry down to 22.5 and 21 mag, respectively). We excluded stars and calculated optical magnitudes for all the galaxies in the field around our targets of interest directly from the DSS plate scans, using Source Extractor software, because not all the objects had magnitudes previously estimated and available in the databases. Furthermore, the identified objects had fluxes estimated in the B_j filter which we converted to the standard Johnson B filter.

3. RESULTS

The main physical parameters of the selected sample of ADF-S galaxies computed by Małek et al. (2017) include dust luminosity, stellar mass, star formation rate (SFR), dust temperature, dust mass and AGN fraction as well as the AGN type. Based on the obtained values, 17 galaxies in the sample were classified as ULIRGs, 22 as LIRGs and the remaining 30 as normal star forming galaxies. Mean values of dust mass, stellar mass, SFR and AGN fraction for each group separately are listed in Table 1.

In all three types if sources an AGN activity is found, but at a higher level in ULIRGs than in LIRGs or star forming galaxies. We found that 63% of our [U]LIRGs have a measurable AGN contribution. As shown in Figure 1, LIRGs and ULIRGs seem to be different types of sources when judged by the AGN activity. For LIRGs, the AGN fraction is not only relatively low, but it remains constant or even slightly decreasing with the increasing star formation rate and dust luminosity, correspondingly. In contrast, in the case of ULIRGs we observe a significant increase of the AGN fraction both with the dust luminosity and star formation rate. As shown in Figure 3, this behaviour is not mirrored by the dependence of the AGN fraction of stellar mass: even if ULIRGs seem to be contain on average more stellar mass (which may be

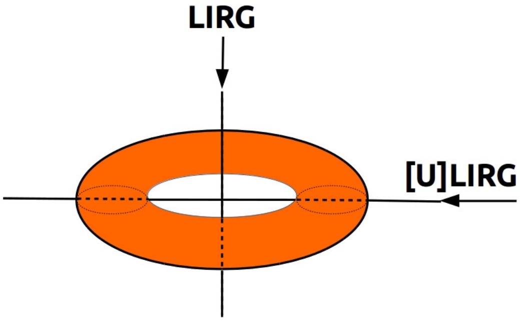

Figure 2. A schematic demonstration of a “geometrical” LIRG/ULIRG scenario: a ULIRG is detected when an AGN is observed edge-on, in which case a surrounding dust increases the IR flux; an AGN observed face-on will be more likely seen as a LIRG.

partially a selection effect), the trend of AGN fraction rising with stellar mass has practically the same slope for both LIRGs and ULIRGs. This indicates that in LIRGs and ULIRGs the present AGN activity is related to the past history of a host galaxy in a similar way (probably through a correlation between a total stellar mass of a galaxy and the mass of the central black hole). However, there is a significant difference between these two classes of sources when it comes to the relation between the present star formation and AGN activity: while these two processes are clearly correlated in ULIRGs, in LIRGs the correlation is not evident.

There is also one more interesting difference between our LIRGs and ULIRGs, and it is the AGN type. While in LIRGs both type 1 and type 2 AGNs are found, ULIRGs harbour type 2 AGNs much more often. There are two possible explanations of this phenomenon. One might be related to the geometry of the source: if we assume the unification scenario of the AGNs, it implies that ULIRGs are mostly galaxies in which we see an AGN edge-on, through a dust torus. A schematic view of such a situation is presented in Figure 2. A weak point of such a scenario is that the radiation of dust is known to be isotropic and it might be difficult to find mechanisms ensuring an increased IR emission in the plane of the torus. An alternative explanation may be based on the fact that the unification scenario of AGNs is still under debate. Then, it may be that type 1 and type 2 AGNs - at least as defined by the Fritz et al. (2006) model incorporated in CIGALE - may be physically, not only geometrically different phenomena.

Table 1. Mean values of the main physical parameters

	$\log(L_{\rm dust})$ [$L_\odot$]	$\log(M_{\rm star})$ [$M_\odot$]	log(SFR) [$M_\odot {\rm yr}^{-1}$]	$\rm AGN_{frac}$ [%]
ULIRGs	12.40 ± 0.32	11.51 ± 0.37	2.53 ± 0.39	19.12 ± 6.76
LIRGs	11.31 ± 0.25	10.95 ± 0.31	1.47 ± 0.20	12.54 ± 3.59
Normal SF	10.35 ± 0.32	10.03 ± 0.50	0.47 ± 0.21	12.82 ± 1.72

NOTE—Dust mass, stellar mass, star formation rate and AGN fraction for ULIRGs, LIRGs and normal star forming galaxies (with $L_{\rm dust} \leq 10^{11} L_\odot$) in the ADF-S estimated by the SED fitting.

Our preliminary measurements of local densities around the ADF-S galaxies also indicate a difference between these two groups of objects. As shown in Figure 4 all the studied objects appear in a large variety local environmental densities. However, we can observe that ULIRGs prefer a certain range of environments with high but not extreme local densities. LIRGs are found both in denser environments and in lower density regions. This might support the hypothesis that the environmental conditions in the outskirts of galaxy clusters (or otherwise mid-density cosmic environments) provide the best conditions for the activation of ULIRGs. As in these environments galaxy mergers are expected to be the most common, this result strengthens the case of galaxy mergers as the trigger of ULIRGs.

4. CONCLUSIONS AND FUTURE PLANS

We present the study of properties of a selected sample of FIR-bright galaxies in the ADF-S field: a significant population of 17 ULIRGs, 22 LIRGs and 30 star forming galaxies with well covered SEDs, fitted with a high reliability by the CIGALE fitter and with either spectroscopic or - mostly - photometric redshifts, also estimated make use of CIGALE (Małek et al. 2014, 2017). We found that a significant part of all these sources bright in the FIR have a non-negligible contribution from an AGN. However, this is particularly visible in the case of ULIRGs among which 63% have a measurable AGN fraction, and this fraction is higher than in the case of LIRGs and normal galaxies. Moreover, in the case of ULIRGs an AGN fraction is rising with the dust luminosity and SFR which indicates a direct relation between the ongoing star formation processes and AGN activity. Such a correlation is not that evident in the case of LIRGs and remaining star forming galaxies. Moreover, while LIRGs contain both type 1 and type 2 AGNs, ULIRGs more commonly harbour Type 2 (edge-on) AGNs. Taken together, this findings may point to two possible scenarios. One scenario, based on the difference

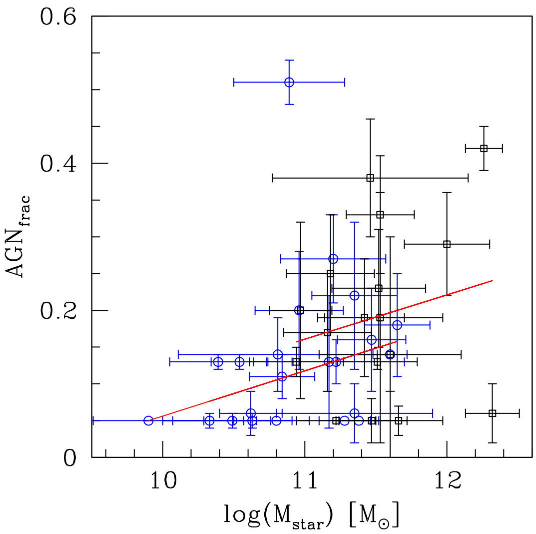

Figure 3. AGN fraction as a function of a galaxy stellar mass. LIRGs are marked by blue open circles, and ULIRGs as black open squares. Red lines indicate linear trends estimated separately for these two groups.

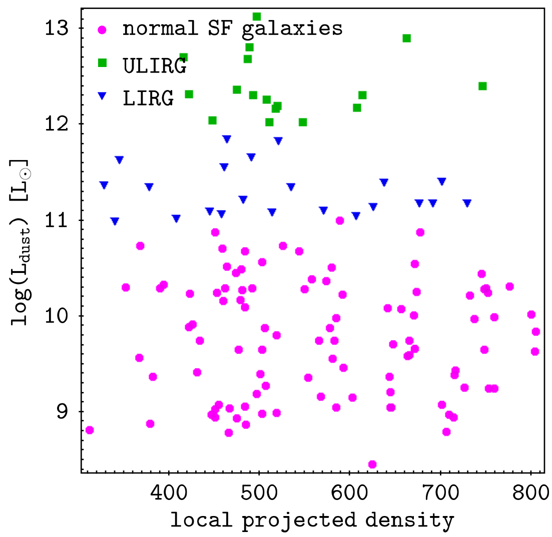

Figure 4. Dust luminosity vs. projected local galaxy density for ADF-S LIRGs, ULIRGs and normal star-forming galaxies. Symbols green squares, blue triangles and pink circles denote ULIRGs, LIRGs and normal star-forming galaxies, respectively.

between AGN types in ULIRGs and other sources, could explain the difference between ULIRGs and LIRGs as purely geometrical: whether we detect an object as a LIRG or ULIRG might depend on an angle from which we see its dusty torus. Another scenario - which, taken all evidence into account, we treat now as more likely - is that the difference between type 1 and type 2 AGNs, at least in these sources, is not just geometrical (as indicated by unification theory of AGNs) but physical, possibly with these two types of sources containing an AGN being in a different phase of its development.

Preliminary measurements of local densities around the ADF-S galaxies, based on the DSS images, indicate that ULIRGs more commonly reside in denser but not extremely dense environments, while LIRGs can be found in a wider range of densities. This finding provides additional evidence for the role of mergers in activation of ULIRGs.

It is obvious that all the analysis presented here would profit significantly from additional observational data, especially in the optical range of the spectrum. A larger number of optical photometric data points would allow to improve the SED fitting in the stellar part of the spectrum and would make possible to obtain such high quality fits for a larger number of ADF-S 90 μm-detected sources. This, in turn, should allow to increase the sample of known LIRGs and ULIRGs in this field. Optical images obtained with modern CCD cameras will allow for measurements of local densities with higher precision than those provided by the DSS scanned plates. We performed observations on the 2 m and 1 m telescopes at the SAAO and acquired the *BVRI* photometry for the fields around the majority of our previously identified [U]LIRGs. The analysis of these new data is ongoing.

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